Ground based LiDAR demonstrates the legacy of management history to canopy structure and composition across a fragmented temperate woodland

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Abstract

The structure of forest canopies correlates with stand maturity and biomass, and develops consistently over time. Remote-sensing technologies such as Light Detection and Ranging (LiDAR) have become prominent tools for measuring structural characteristics of forests.

We walked a portable canopy LiDAR (PCL), an up-facing rangefinder that detects vegetation through the canopy at two kilohertz, along multiple transects at ten different forest stands in the area of Wytham Woods, Oxfordshire, UK. The stands had different species composition, were situated at forest edges and in forest core, were in fragments of different sizes and had different land-use histories. With these data we tested structural differences in vegetation across these stand types.

Although none of the stands have been managed in the last 70 years, they have not converged structurally. Vertical canopy structure differed between stands that regrew naturally from open field and those with a history of coppice management. Forest stands that have developed following major fellings or through spread on to former grazing land showed some structural similarities to classic natural succession from large disturbances. Stands that were actively managed as coppice over preceding centuries, showed a similar structural pattern to mature forest, but without the tall overstorey that can develop into old growth communities.

This structural divergence indicates two distinct pathways for secondary forests: with implications for the future biomass, stand structure, and species composition. The legacy of management practices can determine canopy structure decades after the forest is removed from active management, but can also be difficult to discern with remote sensing data. We recommend that "ground-truthing" remote sensing data go beyond traditional checks of height and topography, as the history and composition of secondary forests can have an important influence on the pace and compositional structure of recovery from management.

Keywords: Canopy structure, LiDAR, Forest fragments, Land-use history, Disturbance.

1. Introduction

Tree canopies exert strong influences on the structure and function of forest ecosystems (Lowman and Rinker, 2004; Shugart et al., 2010). Spatio-temporal

57 variation in the density of a forest canopy can determine understorey light levels
58 (Parker et al. 2002), local climate and microclimate (Shuttleworth et al., 1989;
59 Clinton, 2003), tree regeneration (Barbeito et al., 2009; Bebber et al., 2002), plant
60 and animal community composition (Frelich et al., 2003;Richards and Windsor,
61 2007), and carbon storage (Penne et al., 2010). Quantifying canopy structure and
62 dynamics can therefore address critical questions in forest ecology (Lowman and
63 Rinker, 2004, Wilson 2011). We carried out a quantified analysis of canopy structure
64 as it related to land use history and recovery from active management, which could
65 add to current models of structural regeneration and thus guiding predictions about the
66 pace and direction of forest recovery from anthropogenic disturbance.

67 Forest canopies are highly dynamic, responding to disturbances across spatial
68 and temporal scales. Although forest successional dynamics cover a continuum of
69 disturbance intensity and frequency, natural mechanisms tend to lead to a limited
70 number of trajectories of canopy development observed across many types of
71 temperate broadleaf, close-canopy forests. Gap-phase dynamics are most commonly
72 associated with low-intensity, high-frequency disturbances, such as canopy openings
73 caused by the deaths of individual trees. The resulting small light gaps are filled
74 rapidly by advanced regeneration (i.e., juvenile trees that avoid the gap generating
75 disturbance) and ingrowth from neighbouring trees (Hubbell and Foster 1996;Brokaw
76 1999). Infrequent but high-intensity disturbances (e.g., wind throw, fire, liana-
77 connected tree-fall gaps) remove the canopy of large areas of forest, releasing tree
78 seedlings and saplings from competition for light, allowing incoming seeds to
79 colonize, thus initiating successional trajectories that are often predictable in terms of
80 canopy structure and vertical stratification and which play out across many decades or
81 centuries (Franklin et al., 2002; Ishii et al., 2004; Oliver and Larson, 1996).

Most temperate forests, however, are exposed to or recovering from anthropogenic, rather than natural, disturbances, particularly from land use change and timber management. Furthermore, the response to these disturbances may be different where forest cover is highly fragmented as opposed to largely continuous cover. For example, in the UK, forests have existed only as small isolated patches for centuries due to human activities (FAO, 2010; Rackham, 2001; Whitney, 1996).

The recent availability of remote-sensing technologies offers the potential to make accurate measurements of canopy structure, which allow us to explore different types and intensities of anthropogenic disturbance on canopy structure.

LiDAR technology is a common approach to measuring forest structure (Wulder et al., 2012). LiDAR systems use a range-finder to send and record the return of many pulses of light per second, giving precise estimates of the distance of objects from the source. LiDAR systems on aircraft or satellites can now provide information on forest structure over landscapes and regional scales (Asner et al., 2012; Wulder et al., 2012). Airborne systems, however, are expensive to build, maintain, and schedule for specific studies. An alternative is to use a ground-based system, known as Portable Canopy LiDAR (PCL) (Parker et al., 2004). This system is carried from a front-facing platform at waist height and fires 2000 pulses/ second up through the canopy rather than down on to it. This system captures 'slices' of the canopy instead of 3-dimensional profiles, but it offers a precise, objective, and easily deployed approach to measuring forest structure that is readily translatable to the similar class of technologies used in airborne and satellite systems.

Here, we use a PCL system in forest fragments in the UK to determine if fragment size, edge to core ratio, management history, and composition produce structural patterns similar to those found in the forest successional stages (Fig. 1). Specifically,

we use PCL to test whether 1) woodland core differs in canopy structure from edge, and across fragments of varying sizes and shapes; 2) stand edges influences canopy structure; 3) forests that have been actively managed in the past follow successional recovery in the same way that forests that have grown up on open grazing land.

2. Materials and methods

2.1. Site

Field work was conducted at Wytham Woods, and the surrounding fragments in Oxfordshire, UK (1°20'W 51°47'N) in July and August 2009. Wytham Woods is a relatively large (ca. 400 ha) fragment of mixed woodland, surrounded by numerous other woodland fragments in an agricultural landscape matrix (Fig. 2), typifying the range of woodland sizes and management-histories found in the UK (Kirby and Gibson, 2010 and Supplement A). The wood is situated on a small hill rising to 165 m a.s.l. from the surrounding plain at 60 m a.s.l.

The Woods and fragments show a mixture of origins and management histories (Kirby and Gibson, 2010; Morecroft et al., 2008): ancient semi-natural woodland formerly treated as coppice; other semi-natural woodland regenerated naturally within former wood pasture or on open grazings, and plantations of both broad-leaves and conifers, some of were established on open ground and some within the acient woodland. The semi-natural woodlands are mainly of National Vegetation Classification (Rodwell, 1991) type W8 (*Fraxinus excelsior – Acer Campestre – Mercurialis perennis*).

2.1.1 Permanent sample plots

Permanent sample plots were established in Wytham Woods and surrounding fragments in 2008 and 2009 (Table 1 and Fig. 2) (Supplement A). All stems above 1

cm diameter at 1.3 m height were tagged, mapped, identified to species, and diameter-measured in the 18 ha Wytham core plot (Butt et al., 2009, Butt et al. 2014). In the seven 'satellite' plots, the lower diameter at breast height (DBH) limit was 5 cm. The satellite plots comprised two forest edge plots, and five plots in forest fragments of differing sizes. In addition, five 100 m transects were established in the northern and southern edges of Wytham Wood (Fig. 2).

Each plot was sampled by a series of transects (details in Table 1), totaling 4.5 km. All transects were perpendicular to forest edges except the Southern Edge Fragment, which is long and thin and had only one transect run lengthwise through it (Table 1). The edge plots were sampled perpendicular to the forest boundary for ca. 100 m, beginning 0–2 m from the boundary depending on whether dense, impenetrable vegetation was present which could not be sampled (explained in Section 3).

2.2 Portable Canopy LiDAR (PCL)

Canopy structure data were collected from the plots along the transects using a portable canopy LiDAR system (PLC). The PCL included an up-facing Riegl LD90-3100VHS-FLP range-finder (Riegl USA, Orlando, Florida) attached with battery and small note-book computer to a front-facing platform worn by the surveyer with a harness system. The surveyor walked in a straight line at a consistent pace along the transects, measuring the transects in subsections (5-30 m measurement paths, depending on density of understorey vegetation). The rangefinder recorded distances to nearest object at 2000 pulses/s (i.e. 2kHz of first returns). These returns were then binned into 1 m^2 voxels, which can be thought of as vertically and horizontally binned collections of beam returns, using 1 m bins. We accounted for the tendency of lower objects to receive disproportionally more hits than higher objects (because of occlusion by the lower objects) by applying the MacArthur-Horn

156 transformation to the combined returns for each voxel (MacArthur and Horn, 1969).
157 These transformed voxels results provide an estimate of the canopy height profile
158 (CHP), i.e. the variation in canopy density weith height above ground (Parker et al.,
159 2004) (Fig 1).

160 *2.3. Metrics and statistical analyses*

161 Because of the different units and structure of the data (where some metrics
162 integrate across a transect and others are indicated only by a column of voxels),
163 we conducted four types of analyses: first, we used bootstrapped transect data to
164 find site-differences in LiDAR derived metrics, analyzed the relationship between
165 metrics using mixed effect models where transects were nested within plots, we
166 used t-tests to examine edge effects, and regressed stem data (where available)
167 against site metrics using simple regression across plots. We also build canopy
168 height profiles to examine qualitative differences in comparison to abstracted
169 expectations.

170 Structural metrics describe the vertical and horizontal distribution of LiDAR returns
171 across sites (Parker and Russ, 2004; Parker et al., 2004) and the data for each vertical
172 column in each transect were summarized by the following metrics: Canopy height
173 h_{max} (m), mean highest recorded hit across a site (or the mean of the outer canopy);
174 Rugosity, R (unitless), the standard deviation of the outer canopy, describing the
175 roughness of the canopy surface (Parker and Russ, 2004); Canopy Area Index (CAI)
176 (m^2 m^{-3}) as the sum over all heights of the surface area of the canopy; Shannon's
177 diversity index H, a measure of evenness and occupancy in a column, calculated from
178 the values in each voxel up to h_{max}; and E, the proportion of canopy below the
179 mean, which indicates skewness in the canopy. Statistical comparisons of these
180 metrics across sites were conducted by bootstrapping with replacement the voxel

columns at each site 1000 times (Nordman et al., 2007).

Significance tests of differences between plots in variables other than h_{med} and rugosity (which were site-wide variables and not transects nested in sites) were conducted using Generalized Linear Mixed Models fitted by Penalized Quasi-Likelihood (Venables and Ripley, 2002). Means were fitted for each site with autocorrelated Gaussian errors, and random intercepts for each transect. A correlation analysis of the columnar variables was conducted and Shannon's H was highly correlated with occupancy (r = 0.83), and so was excluded from analyses as occupancy is an easier variable to explain. Edge effects were tested by comparing canopy features in the 5, 10, and 15 m near an edge (when a transect met an edge) to the rest of the transect data using a t-test.

3. Results

There were clear differences in composition and structure between the different areas sampled but these were not obviously related to whether the areas were fragments, edge plots, or core (Tables 1 and 2), although the Northern Edge and Wytham Core did show greater mean height of the outer canopy and canopy occupancy (Fig. 3). When height was taken into account (as through the use of the E Ratio, Wytham Core showed a similarly skewed profile (E_Ratio in Fig. 3) as most other sites (a notable exception being Wood Decay North). Wytham Core also showed high diversity of canopy structure, and North Edge showed greater Rugosity than the other sites.

The only clear difference between the sites was in CAI, which was greater, and less variable, in the Southern than the Northern transects and rugosity, which was higher in the Northern Edge. The Core had the tallest canopy, but h_{max} was not significantly

205 greater than that of the Northern Edge, which had the next-tallest canopy (mean 15.19
206 ± 0.40 m vs. 15.16 ± 0.62 m, t = 0.05, df = 33, p = 0.96). CAI and Occupancy did
207 not differ markedly among sites (Fig. 3), but rugosity was significantly higher in the
208 Northern Edge compared with the other sites (t-test of Northern Edge median vs. other
209 sites, t = 11.3, df = 8, $p < 10^{-5}$). In the correlation analysis, basal area was not
210 correlated with any structure metrics.

211 There were negative relationships between h and the density of tree stems from
212 surveys. This is due to the fact that stem diameter varies negatively with stem density,
213 and positively with tree height. As stands mature, the many initiating stems thin, while
214 the winners grow taller and wider. The negative relationship between rugosity and
215 stem density appears largely due to the Northern Edge plot, which has a tall canopy
216 of similarly sized large ash and relatively few canopy gaps.

217 LiDAR-derived metrics revealed that although there were differ- ences among
218 areas in a number of characteristics there were no clear edge effects at either 5, 10
219 or 15 m), independent of fragment size or composition (p 0.05 in all tests). Thus,
220 where a transect ended at the edge of the forest stand, there were no clear or unique
221 structural features at the transects end compared to areas just before the end. The
222 only features not captured in this analysis, where edges clearly were important,
223 were edges with thick brambles bordering an adjacent open field (i.e., 'sealed'
224 edges). These prohibited measurement, as they were impassable, but the brambles
225 did not extend into the forest or influence forest structure beyond several meters
226 on any transect.

227 As with canopy height, the canopy height profiles (CHP, which show the vertical
228 distribution of vegetation at each site (Fig. 4)) showed again that the two sites
229 that had the least active management histories (Wytham Core [WC] and the

Northern Edge [NE] (Supplement)) had a qualitatively different canopy structure com- pared with the other sites (Fig. 4, results detailed above). The WC CHP was strongly bimodal, with density peaks at 6 m and 16 m. This bimodal distribution was not evident in any of the other plots, which have a single mode at 5–8 m, and declining density at greater heights.

4. Discussion

Forest stands can differ dramatically in vegetation structure and this was detectable using the ground-based LiDAR system. Most methods of remote sensing of forest structure over large extents are achieved though airborne or satellite LiDAR. There have been extensive studies that ground-truthing can work in relatively undisturbed locations. However, few forests have the variety of past land use and depth of knowledge of this use as Wytham Woods. This LiDAR study takes advantage of the focused approach to quantifying the complete vertical structure of stands offered by the PCL method, as well as the extensive history and variety of those measured stands, to investigate whether stand location and fragment size show consistent features independent of historical use and how structural patterns match historical and compositional patterns.

No evidence was found for edge effects on canopy structure, either among plots or within edge transects. The UK has 12% forest cover (>0.1 ha), and this is highly fragmented with 75% of all wood- land parcels being in the range 0.1–2 ha, (Forestry Commission, 2003). Small woodlands (<50 ha) make up 51% of total forest area, and therefore edge effects are thought to be pervasive (Riutta et al., 2014). This makes the lack of apparent edge effects on canopy structure surprising, but perhaps explained by the highly idiosyncratic nature of forest edges (Harper et al., 2005). Wytham has a maintained edge (i.e. there is an

anthropogenic boundary between forest and non-forest), thereby causing the development of a 'side-wall' of dense, shrubby vegetation that 'seals' the edge against ingress of wind and sunlight, and thereby obviates any edge effects of structure further inside the understory (Harper et al., 2005). Indeed, we could not sample the outer boundary of many of the edge transects due to the high density of impenetrable blackthorn (*Prunus spinosa*) and bramble (*Rubus fruticosus*). This, of course, does not indicate a lack of edge effects on the ecology or composition of the forest, merely the structure. Given the importance of historical uses of fragmented forests, it is possible to think of legacies of those histories as the more dominant 'edge effect' than the transition zones in the forest near open fields.

Land use and management history may provide an alternative explanation for the differences between the areas sampled. In the Supplement, we describe in greater detail the differences between site histories. We found a clear pattern related to canopy structure which distinguished among management types, rather than time since management. Coppiced trees lead to a unique canopy structure that tends to be short, dense, and with more uniform composition, even after decades of protection. Wytham Core and the Northern Edge, both with less active management histories than other sites, also have taller heights than other sites. Even when influenced by invasion, such as sycamore presence in Wytham Core, height profiles (both maximum and median height) show a clear difference from sites that have been used for coppicing, even if many decades ago.

Wytham Great Wood, the site of the Core plot, has a high density of sycamore, which appears to have invaded the disturbed woodland. This in contrast to the ancient semi-natural woodlands on the lower slopes at Wytham (Morecroft et al., 2008).

Sycamore is known for its ability to invade open sites with little overstorey or ground-level competition (Hein et al., 2009), so perhaps sycamore succeeded in colonizing gaps in the Wytham Core created by the deaths of large ancient oaks. The fact that even with an invasive pioneer, such as sycamore, the CHP of Wytham Core still appears similar to old growth forest (Perker and Russ, 2004) indicates the difficulty in determining forest composition from structure.

The high density of ash seen in the Northern Edge plot also indicates significant historical spread out from the wood on to former grazing land (albeit with some scattered trees) from which the animals had been withdrawn; ash commonly establishes in disturbed sites both through dispersal of its winged fruit, and by vegetative ingrowth and persistence of stumps (Marigo et al, 2000). Management plans for Wytham from the 1950s point to another cohort of ash establishing at that time on former grassland after the decline of the rabbit population (Kirby and Gibson, 2010). This composition, however is likely to change in the next decade due to the impending introduction into Wytham of ash dieback disease (*Hymenoscyphus pseudoalbidus* V. Queloz (Pautasso et al., 2013)). With upwards of 90% mortality, we expect a significant shift in species composition, and also in canopy structure over the next decade.

The distribution of foliage towards the lower canopy seen in Higgins, Bean Wood and the Southern Edge Fragment might suggest that these are mature forest, in which a shade tolerant understorey is developing. However, these areas are known to have a long history of coppice management with "standards" (i.e. a number of oak trees left to mature for use as timber) (Kirby and Gibson, 2010). The remnant coppice stools, primarily of ash, field maple and hazel, comprise the understorey, while the standards make up the overstorey. Rather than being recent arrivals, some of the coppices are

likely the oldest living organisms in Wytham (Kirby and Gibson, 2010), even though the stems growing from them are quite young.

5. Conclusions

Airborne and space-borne LiDAR are increasingly important tools for characterising forest structure and process over vast regions (Asner et al., 2012; Frolking et al., 2009; Lefsky et al., 2002; Wulder et al., 2012). Although an important component of this monitoring focuses on estimating above-ground biomass using allometries and stand height, in an increasingly large part of the world, forests will not have the allometries shown by undisturbed forest stands. Instead, recovering forests around the world will show the structural legacies of human use due to timber harvest, silviculture, the influx of invasive species, hunting, and other effects, such as coppicing. As ground-truthing remotely-sensed data is essential to validating and interpreting inferred structural variables, we demonstrate here that a new kind of ground-truthing might be required for global assessments of forest health. We show that there is a risk of misinterpreting canopy height profiles if the disturbance history (both natural and anthropogenic) is not under- stood. Portable canopy LiDAR provides a convenient, inexpensive and robust tool to bridge the gap between forest inventories and remote sensing, especially if we are to take into account the myriad ways in which humans interface with forests. For global extrapola- tions of LiDAR-detected vegetation structure, especially when these data will be used to predict trajectories of future structure, we must consider the diverse modes and intensities of disturbance and management within the scope of the classic remote-sensing validation process.

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Tables

Table 1. Plot summary. Type refers to whether the plot is in a forest fragment ("Frag"), on the edge of Wytham Woods ("Edge") or in the center of Wytham Woods ("Core"). These are all designated research plots, and not stands. Area is the total area of the woodland contiguous to the plot. Plot is the area of the plot. Trans is the total number of PCL transects sampled. Length is the total length of those combined transects. Stems is the density of stems >5 cm DBH in the plot. BA is the basal area of those stems. Oaks is the density of large (>70 cm DBH) oak trees in the plot.

Plot	Type	Area (ha)	Plot (ha)	Trans	Length (m)	Stems (ha^{-1})	BA (m^2 ha^{-1})	Oaks (ha^{-1})
Bean Wood	Frag	21.7	1.0	5	680	1505	29.5	10.0
Higgins	Frag	4.8	1.0	3	413	1202	30.8	8.0
North Edge	Edge	361.0	0.96	9	540	854	36.8	3.1
South Edge	Edge	361.0	0.96	1	112	1049	31.8	11.5
South Edge Frag	Frag	0.4	0.32	7	420	1525	38.4	31.3
Stimpsons	Frag	1.2	0.48	3	271	1392	40.7	16.7
Stroud	Frag	9.3	1.0	3	568	1298	38.5	13.0

Wytham Core	Core	361.0	18.0	3	1500	1128	33.3	5.2

446

447 Table 2. Basal area of major species from plot inventory (m^2 ha^{-1}). These species

448 make up > 90 % of the basal area in each of the plots.

Plot	Oak	Ash	Sycamore	Hazel	Field maple	Hawthorn
Bean Wood	16.8	3.8	0.0	5.1	1.6	0.4
Higgins	6.1	11.3	0.0	9.9	2.5	0.2
North Edge	5.2	24.0	0.0	1.4	2.6	3.2
South Edge	8.2	12.5	0.0	0.9	7.0	1.5
South Edge Frag	29.8	0.0	0.0	0.0	0.3	4.1
Stimpsons	16.9	12.3	0.1	7.8	0.6	0.4
Stroud	13.6	9.3	0.0	1.1	11.1	3.0
Wytham Core	6.7	6.7	16.9	0.4	0.2	0.3

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Figures

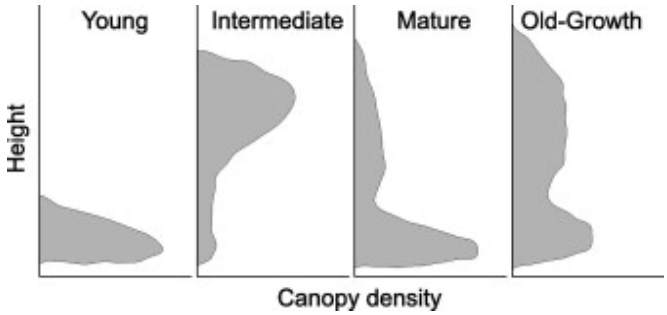


Fig. 1. Abstracted Canopy Height Profiles (CHPs) for Young, Intermediate, Mature and Old-Growth forest stands in the Eastern USA (adapted from Parker and Russ (2004)). Although initial stand formation shows dense, uniform canopy with little understorey, as the forest matures, treefall gaps allow a mix of over and understorey vegetation. Stand maturity in this successional pathway also leads to higher outer canopy.

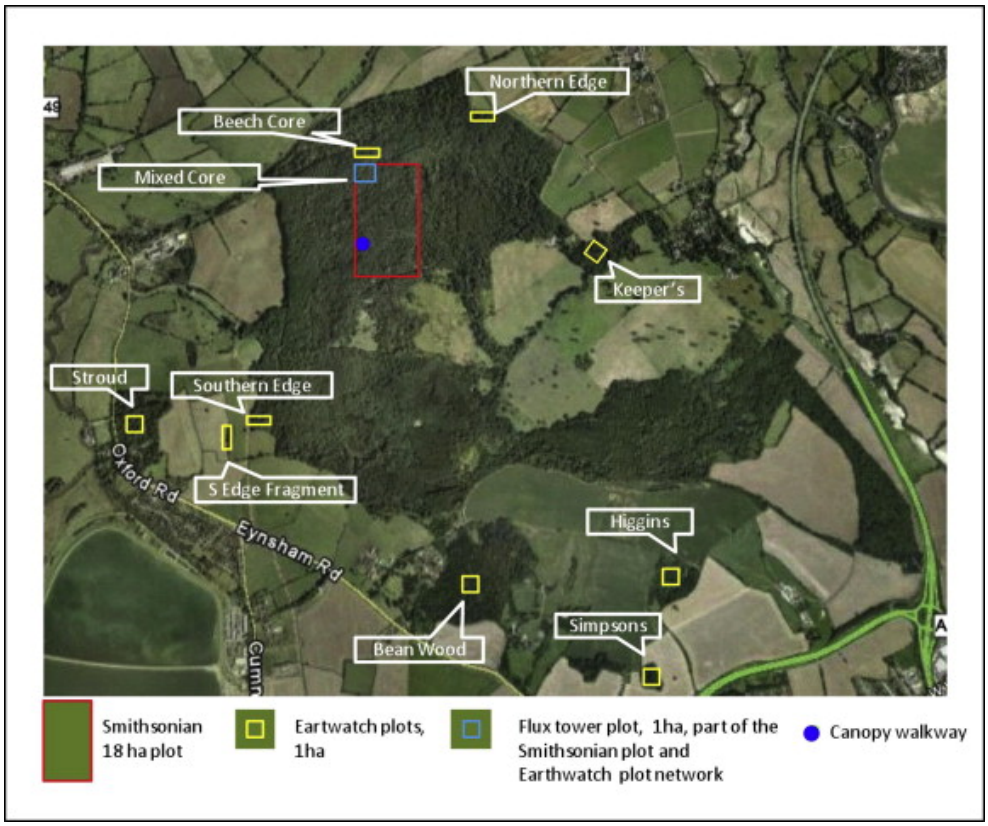
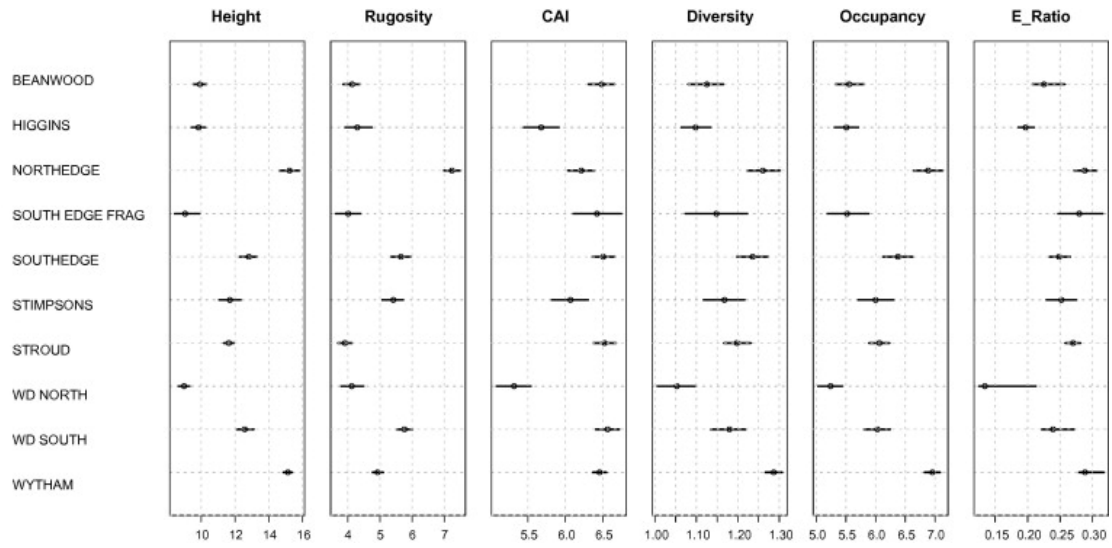


Fig. 2. Map of Wytham Woods core and fragments.



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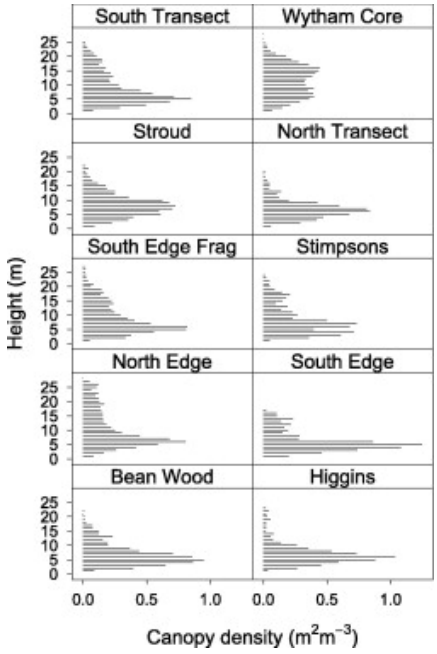
464 Fig. 3. Bootstrapped comparisons of canopy metrics across all sites. 1000 replicate
465 'plots' were simulated. Dots show the median values from the simulations and lines
466 show the 0.025 and 0.975 quantiles of the bootstrapped values.



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468 Fig. 4. Canopy Height Profiles for PCL measurements in the studied plots and
469 fragments. Although the Wytham Core and North Edge show the expected 'mature'
470 stage of forest succession, most fragments show CHPs that are shorter than mature
471 forest, but contain significant understorey.